How *Phytophthora cinnamomi* became associated with the death of *Eucalyptus marginata* – the early investigations into jarrah dieback.

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Short title: Early investigations into jarrah dieback.

Keywords: Koch's postulates, F. D. Podger, soil baiting, selective agar, selective reporting, waterlogging

Abstract

The name jarrah dieback was used in the 1940s to describe a serious economic problem in the jarrah forest in the south west of Western Australia. This was the sudden death of groups of jarrah (*Eucalyptus marginata*) trees that occurred on previously logged sites that had a tendency to become waterlogged in winter. Although the cause was not determined at the time, from symptoms recorded in early investigations the most likely explanation is that the trees died as the result of waterlogging damage. In the 1960s it was shown that many of these sites were infested by the introduced oomycete *Phytophthora cinnamomi* and tree deaths, together with the deaths of many mid- and under-storey plants, were attributed to this pathogen. A chronology of the research, based on contemporary unpublished documents, shows that in 1968 the conclusion that *P. cinnamomi* caused jarrah deaths was not supported by the available evidence, because the work did not satisfy the first and fourth of Koch's postulates. The evidence that *P. cinnamomi* killed many mid- and under-storey plants was much stronger. There are two problems that have been confused: the death of groups of jarrah trees (jarrah dieback) that is caused by waterlogging and the death of many mid- and under-storey plants (Phytophthora dieback) caused by *P. cinnamomi* infection.

Keywords: Koch's postulates, F. D. Podger, soil baiting, selective agar, selective reporting, waterlogging

Introduction

When Frank Podger (1968, 1972) announced that the oomycete *Phytophthora cinnamomi* caused jarrah dieback, it triggered enormous concern amongst foresters and forest pathologists in Australia. Jarrah dieback was the name given in the 1940s to the sudden

death of groups of jarrah (*Eucalyptus marginata*) trees in the south west of Western Australia (Harding 1949; Hamilton 1951). The reason for these deaths had not been determined, in spite of many investigations into possible causes (Harding 1949; Wallace and Hatch 1953; Stahl and Greaves 1959). Within a few years of Podger's discovery, *P. cinnamomi* was associated with tree declines and dieback in other areas of Australasia (Weste and Taylor 1971; Marks *et al.* 1972; Newhook and Podger 1972; Pratt and Heather 1973) and around the world (e.g. Kliejunas and Ko 1975; Lübbe and Mostert 1991; Brasier *et al.* 1993; Tainter *et al.* 2000; Balci and Halmschlager 2003). What was not realised was that Podger's data did not support his conclusion about the role of *P. cinnamomi* in the death of jarrah trees (Davison 2014), although they supported its role in the death of many smaller woody plants. Here I review these early days of jarrah dieback research, based largely on unpublished reports held in the Western Australian Forests Department library (now the library of the Department of Parks and Wildlife) and at the former CSIRO Forest Research Station, Kelmscott, Western Australia.

Jarrah forest and the early years of commercial exploitation

The distribution of jarrah is believed to have originally covered an area of 39 000 km^2 in the south west of Western Australia, although much of this area is now cleared for agriculture (Abbott and Loneragan 1986). The area has a Mediterranean climate with cool wet winters and hot dry summers, with about 90 % of the annual rainfall occurring between April and October. The prime jarrah forest, where jarrah reaches a height of at least 27 m, covers an area of approximately 10 000 km^2, with the highest quality forest occurring on deep lateritic gravel soils on upper and mid slopes of the topographically subdued landscape (Stoate and Helms 1938).

At the beginning of the 19th century the western part of Australia was known to Europeans, but had not been colonised. The British Government was uncertain whether this region had any resources of economic importance. However, following a report of immense forests of magnificent timber in the southern part of what is now Western Australia (Fig. 1), it was annexed to the British Crown in 1829 (Lane Poole 1920). The British Admiralty needed timber for shipbuilding and jarrah was eminently suitable. Large volumes of this timber were exported and this commercial exploitation was extremely important for the development of the state (Fig. 2).

In the early years timber cutting was not regulated. Concessions and leases were granted by the state government giving millers the right to remove and export timber for a nominal rent (Lane Poole 1920). By the time the Western Australian Forests Department was formed in 1918 almost all of the high quality stands of jarrah in the northern forest had been logged (Abbott and Loneragan 1986). By 1920 it was estimated that nearly 1 million acres [4 600 km^2] had been cut over (mainly in the northern jarrah forest), more than750 million cubic feet [21 million m^3] of logs removed, and the forest canopy had been reduced by almost 50 % (Wallace 1966). These changes in leaf area resulted in rising superficial water tables, for example with paperbark flats becoming swamps, and free water being present in winter in areas that had previously been dry. Jarrah crowns deteriorated becoming ‘a gaunt framework of limbs which were dead some 20 feet [6 m] from their extremities’ (Stoate and Bednall undated). Crown deterioration was believed to be a consequence of rising winter water tables, together with damage resulting from severe fires fuelled by logging debris (Stoate and Bednall undated; Wallace and Hatch 1953; Wallace 1966). Following its establishment, the activities initiated by the Western Australian Forests Department attempted to reverse these trends through fire management including an initial exclusion policy, by developing working

plans, and by using tree marking under group selection to regulate cutting (Williamson *et al.* 2005).

Jarrah dieback

Background

By the mid-1940s, just after World War II, there was a new problem that concerned the Western Australian Forests Department; this was groups of dying jarrah trees that became known as jarrah dieback (Fig. 3). The first observation of a group of dying trees was made in 1921 (Wallace and Hatch 1953) but by the 1940s these were much more numerous; they were associated with sites with winter waterlogging (Stoate and Bednall undated). There was uncertainty as to whether this was another manifestation of crown deterioration, or whether it was something quite different (Wallace and Hatch 1953). Although the total area where these deaths were occurring was quite small, the patches of dead trees were numerous, and this problem was seen to be of great economic importance for maintaining the supply of jarrah timber for export. Even though at this time both money and manpower would have been in short supply, the Forestry and Timber Bureau in Canberra (FTB) and the Western Australian Forests Department jointly established a research station at Dwellingup to investigate the cause of these deaths (Forests Department 1947).

Charlie Hamilton was the first appointee, and worked at Dwellingup from November 1947 to July 1948 (Hamilton 1951). He showed that these dying jarrah patches occurred on previously logged sites in the northern jarrah forest. The deaths were associated with definite topographical features: in gully heads, on saddles and along the upper sections of drainage channels. They were in poorer quality forest, on black, heavy lateritic gravels and yellow

brown gravels below heavy lateritic caps. Deaths were occurring rapidly, and all ages and size classes were affected. Jarrah was the only tree affected. Marri (*Corymbia calophylla*) that co-occurs with jarrah did not die, but a number of other plants particularly *Banksia grandis*, also died, resulting in significant floristic change. He also mentioned that in one intensively monitored area there was free water on the soil surface during winter. Hamilton's observations were confirmed and extended by others. Hugh Waring (1950) commented on the death of *Allocasuarina fraseriana* in addition to *Banksia grandis,* he provided photographs of affected areas, and speculated that the deaths might have been caused by toxic soil conditions, and that impeded drainage might be involved. Owen Loneragan (1961) also commented on the association of deaths with exposed ridges and flooded gullies and suggested that waterlogging might be important.

There were a number of investigations into the cause of these jarrah deaths. John Harding (1949) found no evidence that the deaths were caused by pests or pathogens. The only unusual feature he noted was that more tyloses and extensive gummosis was present in sapwood from affected, compared with unaffected trees. Roy Wallace and Alan Hatch (1953) compared the physical and chemical properties of soils from affected and unaffected sites, and found no major differences. The investigations did not appear to be getting anywhere. Even though jarrah deaths continued, during the next decade the direction of research changed, with more emphasis being placed on litter decomposition, nutrition and jarrah phenology (Forests Department 1953, 1958).

In 1959 the FTB initiated further work on jarrah dieback by appointing Frank Podger, a forester in the Western Australian Forests Department, as a research officer to work at the Dwellingup Research Station (Forestry and Timber Bureau 1959). The FTB also sent their forest pathologist (Bill Stahl) and forest entomologist (Ron Greaves) to Western Australia for

a 2 week visit to again investigate whether pests or pathogens were involved (Podger 1959a). Stahl, Greaves and Podger together inspected affected stands and examined foliage, stems and roots of jarrah and the mid- and under-storey plants *B. grandis*, *Macrozamia reidlei* and *Persoonia longifolia* (Stahl and Greaves 1959). There was no evidence that the deaths resulted from insect damage and there were no consistent fungal lesions. The only abnormalities noted in jarrah were that there were excessive tyloses in the sapwood, and there was a thin sheet of kino just below the surface of the sapwood. Consequently, when Podger (1959b) completed a review of possible causes of jarrah dieback he concluded that the most likely cause was environmental change as a result of previous heavy cutting, the exclusion of fire from some regions and the increase in, and incidence of, severe fires. Environmental changes might result in a decrease in nutrient availability, an increase in soil salinity or ion toxicity and changes to the water relations of the site. Podger investigated all of these possible changes using a combination of field studies and pot experiments.

Podger quickly dismissed the possibility that jarrah dieback resulted from increased salinity or metal ion toxicity, based on the observations of others and his own research (Podger 1966a). In 1962 he thought that jarrah deaths were unlikely to result from drought because of jarrah's ability to survive the severe summers of 1960-61 and 1961-62 (Podger 1962). He supported this conclusion with pot experiments conducted in 1963, that showed that jarrah was less sensitive to water deficiency than the other jarrah forest trees (*C. calophylla*, *E. accedens*, *E. megacarpa*, *E. patens*, *E. rudis* and *E. wandoo*) (Podger 1967a). In 1963 he also conducted pot experiments on jarrah's waterlogging tolerance, and showed that it was substantially less tolerant than other forest eucalypts (Podger 1963), however he rejected waterlogging as a cause of jarrah dieback because it had recently appeared in essentially undisturbed forest and in well-drained soil on steep (28°) slopes, and waterlogging did not

explain the death of many of the mid- and under-storey species (Podger 1967b). Also by 1963, Podger's investigation had taken another direction.

Search for *Phytophthora*

In 1962 Podger investigated several cases of shelterbelt mortality of *Pinus radiata* on the Swan Coastal Plain (Podger 1962). This drew his attention to similar mortality of *P. radiata* in New Zealand (Newhook 1959) and little leaf disease of *P. echinata* in the United States (Campbell 1951; Zak 1961); both of these problems were associated with *Phytophthora* spp. These reports were of pathogens that had a wide host range, were difficult to isolate, and primarily attacked fine roots. Podger wondered whether a phytophthora might be the cause of jarrah dieback (Podger 1962, 1968, 1972).

In December 1962 Podger started a series of pot experiments using sterilised and unsterilised soil from affected and unaffected forest areas. He found that seedlings in unsterilised soil from dieback areas developed root rot and some died (Podger 1963). He arranged for Ralph Doepel (Western Australian Department of Agriculture) to help because he realised that he would need assistance from an experienced plant pathologist to conduct the isolation and identification of *Phytophthora* (Podger 1963). During the winter and spring of 1963 they excavated mature trees from three forest stands where jarrah trees were showing crown decline, but were not dead. At each stand they started by examining the trunk, and then traced out along major roots followed by smaller roots, sampling pieces of apparently healthy and dying roots (R. F. Doepel pers. comm. 13 August 1980). The samples were plated out onto a range of agars including 3P agar which is selective for *Phytophthora* (Eckert and Tsao 1962). Soil and roots were also inserted into apples into an attempt to isolate *Phytophthora* (Podger *et al.* 1965). All cultures were sent to the Commonwealth Mycological Institute in

London for authoritative identification. No known pathogens were identified (Doepel and Podger undated).

Podger and Doepel continued with the pot experiments using soil from dieback and healthy forest areas. There appeared to be a biological factor in the soil that caused seedling deaths, because losses could be reduced by steaming the soil, sterilising it with formalin, or treating it with thiram drench. But they were unable to isolate a *Phytophthora* (Podger 1964; Podger *et al.* 1965). In October 1964 George Zentmyer (Professor of Plant Pathology, University of California, Riverside Campus, who was on sabbatical leave at the Waite Agricultural Research Institute, South Australia), a *Phytophthora* specialist, visited Podger and Doepel at the Department of Agriculture in Western Australia. Zentmyer had plates of 3P agar with him, and attempted isolations from seedling roots from the pot experiments. He returned to the Waite Institute, and found that he had isolated *P. cinnamomi* (Zentmyer 1964).

Once *P. cinnamomi* had been isolated by Zentmyer, Doepel used similar techniques (plating onto 3P agar and baiting soil with avocado fruit) to isolate it from soil and plant roots from both the pot trials and the forest (Podger 1964). Pathogenicity tests showed that it could infect and kill seedlings of jarrah and *B. grandis*, but not *C. calophylla* (Podger 1965; Podger *et al.* 1965). *P. cinnamomi* appeared to be an introduced pathogen (Podger *et al.* 1965).

Over the next months, using a lupin baiting technique, Podger showed that *P. cinnamomi* could be isolated from soil from 27 affected jarrah stands and three affected banksia woodland stands, but not from 344 soil samples from unaffected stands. He also isolated it from 31 species from the forest, including jarrah (Podger 1965). He showed that soil conditions of both temperature and moisture would be suitable for sporulation from July until late spring (probably November). In early 1965 Podger was saying that he had solved the problem, and that changes to forestry practice would be needed to minimise the spread of *P.*

cinnamomi (R. J. Underwood pers. comm. 30 July 2014). By 1966 he stated that he had the final proof that *P. cinnamomi* was the prime cause of jarrah dieback (Podger 1966b). He had shown that *P. cinnamomi* was capable of activity over the whole range of climatic conditions, soils and forest conditions in the jarrah forest. He stated that movement of infested soil would spread the pathogen, and suggested that there would need to be modifications of logging and roading practices in order to minimise spread. He had also deliberately infested 26 unaffected forest areas with either cultures or infested soil, and reproduced symptoms of jarrah dieback in 14 of these areas; no symptoms occurred in 26 control sites (Podger 1966b).

In March 1966, Erik Björkman (Professor of Forestry, Royal College of Forestry, Stockholm, Sweden) and Stahl (FTB) visited the jarrah forest. Björkman's visit was at the invitation of the FTB and he was asked to comment on Podger's investigations. Unfortunately Podger was overseas at the time and not able to answer Björkman's questions in person. Björkman accepted the involvement of *P. cinnamomi* in the death of jarrah and banksias, but suggested that it might not be the primary cause of tree death and that waterlogging and other soil or silvicultural conditions might also be important (Björkman 1966). He also questioned whether *P. cinnamomi* was introduced, suggesting that it could be widespread but dormant in apparently unaffected forest. Podger (1966c) responded vigorously to Björkman's comments rejecting the suggestion that *P. cinnamomi* was not the primary cause of jarrah dieback. He also used the results of his extensive soil sampling programme to support his conclusion that *P. cinnamomi* was an introduced pathogen. Podger's arguments were widely accepted in Western Australia.

Actions by the Western Australian Forests Department

The investigations into jarrah dieback were undertaken collaboratively by the Western Australian Forests Department and the FTB. Initially FTB officers were accommodated at

the Dwellingup Research Station, but this was burnt down in a severe fire in 1961 (Forests Department 1961). Although Podger continued at Dwellingup following the Dwellingup fire, in 1964 he moved into a custom built FTB Forest Research Institute at Kelmscott, closer to Perth.

Podger's explanation (Podger 1966b) that *P. cinnamomi* was the prime cause of jarrah dieback was accepted in good faith by the Western Australian Forests Department (Harris 1965, Forests Department 1967). By the time this became public knowledge, the Forests Department had constructed new research facilities in Perth, Dwellingup and Manjimup (Wallace 1969). The equivalent of six full time research officers were working on different aspects of the disease: mapping its extent, measuring rate of spread, screening alternative timber species, evaluating environmental factors and investigating control measures (Batini 1973; Christensen 1975; Shea 1975). In addition the Forests Department invited Zentmyer and Frank Newhook (Professor of Plant Pathology, University of Auckland) to visit Western Australia in 1968 and provide advice on the research programmes being undertaken, which they broadly supported (Newhook 1968; Zentmyer 1968).

Concern about the role of *P. cinnamomi* as the cause of eucalypt death and decline spread from Western Australia to other states in Australia. The number of researchers working on this pathogen in native vegetation had increased from one in 1966 to the equivalent of 15 in 1971 (Newhook and Podger 1972), and a major conference on eucalypt dieback in Australia was held at Lakes Entrance, Victoria in 1973. During the 1970s *P. cinnamomi* dominated research in forest pathology throughout Australia.

The failure to address Koch's postulates in jarrah

Although Podger was confident that he had determined that *P. cinnamomi* was the cause of jarrah dieback (Podger 1966b) his approach was not that of a plant pathologist, it was back to

front. He had used soil baiting to show that jarrah deaths were associated with infested sites on soils with impeded drainage (Podger *et al.* 1965). He had shown that *P. cinnamomi* could infect and kill jarrah and banksia seedlings in pot experiments (Podger *et al.* 1965). He had shown that he could isolate *P. cinnamomi* from many different plants including jarrah (Podger 1965, 1968, 1972). He had also deliberately infested 26 field plots, with symptoms of jarrah dieback developing in 14 (Podger 1966b). However, what he had not done was satisfy the first of Koch's postulates by showing a constant association between infection of jarrah trees by *P. cinnamomi* in the forest, and jarrah deaths.

Between 1965 and 1968 Podger conducted a large sampling programme to try to satisfy the first of Koch's postulates; his approach was unusual. Rather than inspecting roots for lesions and sampling from these, he plated root pieces directly onto *Phytophthora*-selective agar. Out of the 100 jarrah trees sampled he isolated *P. cinnamomi* from only five (at Willowdale, East Kirup and Karnet). Isolation frequencies for *B. grandis* were much higher with *P. cinnamomi* being recovered from 29 % of the 121 plants sampled (Davison 2011). It is unfortunate that he did not report this 5 % recovery rate from jarrah to the FTB, the Western Australia Forests Department, or in his publications (Podger 1968, 1972).

Zentmyer (1968) suggested that the low recovery of *P. cinnamomi* was because it caused a fine root necrosis, whereas the higher recovery from banksias was because it was able to invade much larger roots. Zentmyer's explanation was accepted without question (Batini and Hopkins 1972), even though fine root infection had not been demonstrated by direct plating of jarrah roots collected in the field. This explanation was based on soil baiting.

Podger does not appear to have recognised the limitations of the methods that he used. Soil baiting is very useful, but only indicates whether the soil is infested, it does not determine whether roots of any or all species in the soil sample are infected. Similarly, selective agar is

very useful for separating the organism of interest from a mixture of other microorganisms, but it needs to be supported by plating onto non-selective media otherwise it is impossible to determine what other potential pathogens are present.

There was another problem with Podger's data. In 1966 he had conducted field inoculations with both cultures and infested soil in 26 plots at three field sites (Podger 1972) and had reproduced symptoms of disease at 14 of these plots, but not in the 26 control plots (Podger 1966b). The symptoms that developed 18 months later were deaths in mid- and under-storey plants, members of the Proteaceae and Dilleniaceae (Podger 1972). Between 1968 and 1971 two of these three field sites were destroyed by salvage logging and pole cutting, but at the remaining site, a perched water table site, one jarrah tree died. There is no mention of any attempts to directly isolate *P. cinnamomi* from roots of symptomatic plants; the re-isolations were done by lupin baiting soil samples (Podger 1972). This procedure does not satisfy the fourth of Koch's postulates.

Although Podger (1972) asserted vigorously that he had shown that *P. cinnamomi* caused jarrah dieback and similar disease in natural vegetation in Western Australia, his work was not as rigorous as appears at first sight. His failure to demonstrate a constant association between infection of jarrah trees by *P. cinnamomi* and tree death is an important shortcoming, as is his failure to report this. Similarly, although the field inoculations reproduced deaths in native vegetation, no evidence is presented that the plants were infected. There was an over-reliance on soil baiting and the use of selective agar without an appreciation of the shortcomings of these methods.

Discussion

Podger (1972) argued that jarrah dieback was a single problem that was caused by *P. cinnamomi* and which affected a large number of the indigenous species in the south west of Western Australia. He extended the meaning of the name jarrah dieback to include many mid- and under-storey plants that died on infested sites, so it was no longer primarily a forestry problem, but one of the whole ecosystem. As he noted, infested areas occur in banksia woodlands and on sandplains, and in Western Australia the name has been changed from jarrah dieback to Phytophthora dieback (Department of Conservation and Land Management 2003) to better reflect widespread concern about deaths occurring on infested sites in areas outside the jarrah forest.

Podger's change in the definition of jarrah dieback has the potential to confuse because it ascribes a common cause to all deaths, even though, as explained above, his observations and research did not support this. This confusion is evident in his references to jarrah dieback because it is unclear whether he was referring to the death of jarrah trees, to the death of the mid-and/or under-storey vegetation, or both. An example is when he reported that he had reproduced symptoms of jarrah dieback in 14 of 26 infested plots (Podger 1966b), but these were deaths of mid- and under-storey species, it was only much later that a single jarrah tree died (Podger 1972).

In my opinion his great contribution to plant pathology was to conceive that a *Phytophthora* might be involved, and despite many failures, to persist with attempts to demonstrate this. His data for *P. cinnamomi* causing the death of mid- and under-storey plants such as banksias are more convincing than his evidence for it killing jarrah trees. However in the mid-1960s the main forestry concern was about the economic importance of jarrah timber; there would have been less interest in the role of *P. cinnamomi* in killing other native plants in an area of great botanical diversity (Cahill *et al.* 2008). His selective reporting is understandable, but inexcusable.

No one with skills in diagnostic plant pathology appears to have checked Podger's interpretation at that time. There was a failure by plant pathologists to recognise the limitations of the methods used, and to ask questions about sample sizes and isolation frequencies. During the 1970s his soil baiting method was widely used in eastern Australia to raise concern that the presence of *P. cinnamomi* would lead to tree decline and dieback (Weste and Taylor 1971; Marks *et al.* 1972; Pratt and Heather 1973). Even the observations that there did not appear to be extensive fine root necrosis of jarrah in forest trees (Shea *et al.* 1980; Shea and Dell 1981) did not raise questions about how jarrah was infected and how the trees died.

From the weather records, which show that the 1940s to 1960s were exceptionally wet (Commander 2014, Davison 2014), the site characteristics and site histories where jarrah trees died (Waring 1950; Hamilton 1951; Loneragan 1961), the lack of pathogenic lesions (Harding 1949; Stahl and Greaves 1959; Doepel and Podger undated; Podger *et al.* 1965), the known sensitivity of jarrah to waterlogging (Podger 1967b; Davison and Tay 1985) and the symptoms of tylosed sapwood (Harding 1949; Stahl and Greaves 1959) which are caused by waterlogging (Davison and Tay 1985), the most credible explanation is that the jarrah trees died from waterlogging damage. Podger rejected this explanation because he noted deaths in essentially undisturbed forest and on well-drained soil on steep slopes (Podger 1967b). Without knowing whether he was referring to jarrah or mid- or under-storey deaths and without an examination of the sites, it is not possible to determine whether forestry activities up-slope would have changed drainage patterns, or dykes in the soil profile would have caused waterlogging at depth (Buehrig and Shearer 1991). Jarrah deaths from waterlogging were recorded up-slope of such a dyke in 1993 (Davison 1997).

Many of the sites where jarrah trees died would undoubtedly have also been infested by *P. cinnamomi* because the early reports mention that *B. grandis* died before jarrah trees (Waring

1950; Hamilton 1951; Wallace and Hatch 1953). Banksias are extremely susceptible and are used as indicators of site infestation (Brandis 1983). However, it is likely that there would also have been some uninfested sites where jarrah died. Podger (1968) mentions one such site, where jarrah died but *B. grandis* was still alive, so this must have been uninfested. Also Waring (1950), and Wallace and Hatch (1953) mention that *Allocasuarina fraseriana* died before jarrah if it was present on the site. This is surprising because present experience (E. Brown pers. comm. 8 May 2014) is that *A. fraseriana* is not very susceptible to *P. cinnamomi* and is an unreliable indicator of site infestation. Its sensitivity to waterlogging is unknown, but if it shows similar sensitivity to jarrah this would indicate that some sites were waterlogged but not infested.

Learning the history of the jarrah dieback investigations indicates that there are still problems to be resolved. The first is terminology. Confusion has arisen because the name jarrah dieback has been applied to at least two problems, I suggest that it reverts to its original meaning, of groups of jarrah trees that die and decline on sites with a tendency to become waterlogged following exceptionally heavy rainfall, with deaths resulting from waterlogging damage. I suggest that the name Phytophthora dieback is reserved for the death of mid-and under-storey plants resulting from infection by *Phytophthora* spp. Separating these two problems is important because managers need an accurate diagnosis so that their management is correctly targeted.

The Legacy

Foresters in the 1960s and 1970s responded to Podger's assertions that *P. cinnamomi* killed jarrah trees by developing a suite of novel, innovative management practices aimed at identifying infested areas, identifying risk, and minimising spread (Batini and Cameron 1971;

Batini 1976; Bradshaw and Chandler 1978; Underwood and Murch 1984). These practices have been applied to the management of forested areas, national parks, nature reserves, and mining. They have been widely adopted in other parts of Australasia and throughout the world. Their application in Western Australia has minimised the spread of *P. cinnamomi* in this botanically rich area. Foresters can be justly proud of their achievements.

Acknowledgements

I thank D. M. Griffin for drawing my attention to the low recovery of *P. cinnamomi* from jarrah, to J F Titze for access to documents at the CSIRO Forest Research Station Kelmscott in 1980, to CSIRO for allowing me to publish Podger's isolation data following his death, and to L. Wright for assistance with tracing documents. F. E. Batini, M. C. Calver, E. O'Gara and G. StJ. Hardy are thanked for providing feedback on the manuscript.

References

Abbott I, Loneragan O (1986) Ecology of jarrah (*Eucalyptus marginata*) in the northern jarrah forest of Western Australia. Bulletin of the Department of Conservation and Land Management, No. 1. Perth, Western Australia.

Balci Y, Halmschlager E (2003) *Phytophthora* species in oak ecosystems in Turkey and their association with declining oak trees. Plant Pathol 52:694-702.

Batini FE (1973) Jarrah dieback – A disease of the jarrah forest of Western Australia. Bulletin 84, Forests Department of Western Australia. Perth.

Batini FE (1976) Quarantine in native forests. Information sheet 35, Forests Department of Western Australia. Perth.

Batini FE, Cameron JN (1971) Some aspects of logging hygiene. Research Paper No. 3. Forests Department of Western Australia. Perth.

Batini FE, Hopkins ER (1972) *Phytophthora cinnamomi* Rands – A root pathogen of the jarrah forest. Aust For 36:57-68.

Björkman E (1966) On the jarrah (*Eucalyptus marginata*) dieback in Western Australia – its cause and control. Unpublished manuscript, Department of Parks and Wildlife Library, Perth.

Bradshaw FJ, Chandler RJ (1978) Full coverage at large scale: large-scale under-cloud 70 mm colour aerial photography for detecting and mapping a disease in the forest understorey over extensive areas. American Society of Photogrammetry; Symposium on Remote Sensing for Vegetation Damage Assessment, Seattle, Washington, Feb 14-16. pp 267-290.

Brandis AJ (1983) Introduction to the detection and interpretation of the symptoms of jarrah dieback disease in Western Australia. Technical Paper No. 3, Forests Department of Western Australia. Perth.

Brasier CM, Robredo F, Ferraz JFP (1993) Evidence for *Phytophthora cinnamomi* involvement in Iberian oak decline. Plant Pathol 42: 140-145.

Buehrig RM, Shearer BL (1991) Geomorphology and the environment in the northern jarrah forest of Western Australia. Department of Conservation and Land Management, Perth.

Cahill DM, Rookes JE, Wilson BA, Gibson L, McDougall KL (2008) *Phytophthora cinnamomi* and Australia's biodiversity: impacts, predictions and progress towards control. Aust J Bot 56:279-310.

Christensen P (1975) Jarrah dieback – Soil temperature and moisture regimes of some southern forest types. Bulletin 88, Forests Department of Western Australia. Perth.

Commander DP (2014) Drought and flooding rains: Western Australian water resources at the start of the21st century. J Roy Soc Western Australia 97:221-235.

Davison EM (1997) Are jarrah (*Eucalyptus marginata*) trees killed by *Phytophthora cinnamomi* or waterlogging? Aust For 60:116-124.

Davison EM (2011) How do *Phytophthora* de Bary species kill trees? NZ J For Sci 41S:S25-S37.

Davison EM (2014) Resolving confusions about jarrah dieback – don't forget the plants. Australas Plant Pathol 43: 691-701.

Davison EM, Tay FCS (1985) The effect of waterlogging on seedlings of *Eucalyptus marginata*. New Phytol 101:743-753.

Department of Conservation and Land Management (2003) *Phytophthora cinnamomi* and disease caused by it. Volume 1 – Management Guidelines. Department of Parks and Wildlife, Perth.

Doepel RF, Podger FD (undated) Jarrah blight investigations. Report on progress in cooperative pathological investigations. Unpublished manuscript, Department of Parks and Wildlife Library, Perth.

Eckert JW, Tsao PH (1962) A selective antibiotic medium for isolation of *Phytophthora* and *Pythium* from plant roots. Phytopathology 52:771-777.

Forestry and Timber Bureau (1959) Annual Report. Canberra: Govt. Print..

Forests Department (1947) Report on the operations of the Forests Department for the year ending 30 June 1947. Perth.

Forests Department (1953) Report on the operations of the Forests Department for the year ending 30 June 1953. Perth.

Forests Department (1958) Report on the operations of the Forests Department for the year ending 30 June 1958. Perth.

Forests Department (1961) Report on the operations of the Forests Department for the year ending 30 June 1961. Perth.

Forests Department (1967) Report on the operations of the Forests Department for the year ending 30 June 1967. Perth.

Hamilton CD (1951) The dying of jarrah (*E. marginata*) in Western Australian forests. Progress of work done to July 1948. Unpublished manuscript, Department of Parks and Wildlife Library, Perth.

Harding JH (1949) Pathogenic aspects of die back in the jarrah forest of Western Australia. Australian Forestry Conference. Unpublished manuscript, Department of Parks and Wildlife Library, Perth.

Harris AC (1965) Seminar on jarrah dieback. Briefing notes for seminar at Harvey 19-20 October 1965. Unpublished manuscript, Department of Parks and Wildlife Library, Perth.

Kliejunas JT, Ko WH (1975) Association of *Phytophthora cinnamomi* with ohia decline on the island of Hawaii. Phytopathology 66:116-121.

Lane Poole CE (1920) Notes on the Forests and Forest Products and Industries of Western Australia. Forests Department of Western Australia. Perth, Western Australia.

Loneragan OW (1961) Jarrah (*Eucalyptus marginata* Sm.) and karri (*Eucalyptus diversicolor* F.v.M.) regeneration in southwest Western Australia. M.Sc. Thesis, University of Western Australia.

Lübbe WA, Mostert GP (1991) Rate of *Ocotea bullata* decline in association with *Phytophthora cinnamomi* at three study sites in the Southern Cape indigenous forests. S African For J 159:17-24.

Marks GC, Kassaby FY, Reynolds ST (1972) Die-back in the mixed hardwood forests of Eastern Victoria: a preliminary report. Aust J Bot 20:141-154.

Newhook FJ (1959) The association of *Phytophthora* spp. with mortality of *Pinus radiata* and other conifers. I. Symptoms and epidemiology in shelterbelts. N Z J Agric Res 2:808-843.

Newhook FJ (1968) Report on visit to Western Australian jarrah dieback area. 28 April – 4 May 1968. Unpublished report to the Forests Department WA, May 1968, Department of Parks and Wildlife Library, Perth.

Newhook FJ, Podger FD (1972) The role of *Phytophthora cinnamomi* in Australian and New Zealand forests. Ann Rev Phytopath 10: 299-326.

Podger FD (1959a) Annual report to the Forestry and Timber Bureau. Unpublished manuscript. [Viewed February 1980]

Podger FD (1959b) A review of the disorder jarrah dieback. Station Resport no. 1 – December 1959. Forestry and Timber Bureau. Forest Experimental Station. Dwellingup. Unpublished manuscript, Department of Parks and Wildlife Library, Perth.

Podger FD (1962) Annual report to the Forestry and Timber Bureau. Unpublished manuscript. [Viewed February 1980]

Podger FD (1963) Annual report to the Forestry and Timber Bureau. Unpublished manuscript. [Viewed February 1980]

Podger FD (1964) Annual report to the Forestry and Timber Bureau. Unpublished manuscript. [Viewed February 1980]

Podger FD (1965) Annual report to the Forestry and Timber Bureau. Unpublished manuscript. [Viewed February 1980]

Podger FD (1966a) Research Project W.A.4 – The cause of jarrah dieback. Progress Report no. 1 – A consideration of some earlier hypotheses of cause – Nutrient decline, Soil salinity, Metal ion toxicity. Forest Research Institute, Western Regional Station,

Kelmscott, WA. Unpublished manuscript, Department of Parks and Wildlife Library, Perth.

Podger FD (1966b) Annual report to the Forestry and Timber Bureau. Unpublished manuscript. [Viewed February 1980]

Podger FD (1966c) On the jarrah (Eucalyptus marginata) dieback in Western Australia – its cause and control. Unpublished manuscript, Department of Parks and Wildlife Library, Perth.

Podger FD (1967a) Research Project W.A.4 – The cause of jarrah dieback. Progress Report no. 2 – A consideration of some earlier hypotheses of cause – Drought. Forest Research Institute, Western Regional Station, Kelmscott, WA. Unpublished manuscript, Department of Parks and Wildlife Library, Perth.

Podger FD (1967b) Research Project W.A.4 – The cause of jarrah dieback. Progress Report Number 3 – Waterlogging as a possible cause. Forest Research Institute, Western Regional Station, Kelmscott, WA. Unpublished manuscript, Department of Parks and Wildlife Library, Perth.

Podger FD (1968) Aetiology of jarrah dieback. A disease of the dry sclerophyll *Eucalyptus marginata* Sm. forests in Western Australia. M.Sc. Thesis, University of Melbourne.

Podger FD (1972) *Phytophthora cinnamomi*, a cause of lethal disease in indigenous plant communities in Western Australia. Phytopathology 62:972-981.

Podger FD, Doepel RF, Zentmyer GA (1965) Association of *Phytophthora cinnamomi* with a disease of *Eucalyptus marginata* forest in Western Australia. Plant Dis Reporter 49:943-947.

Pratt BH, Heather WA (1973) The origin and distribution of *Phytophthora cinnamomi* Rands in Australian native plant communities and the significance of its association with particular plant species. Aust J Bot 26:559-573.

Shea SR (1975) Environmental factors of the northern jarrah forest in relation to pathogenicity and survival of *Phytophthora cinnamomi*. Bulletin 85, Forests Department of Western Australia. Perth.

Shea SR, Dell B (1981) Structure of the surface root system of *Eucalyptus marginata* Sm. and its infection by *Phytophthora cinnamomi* Rands. Aust J Bot, 29:49-58.

Shea SR, Gillen KJ, Leppard WI (1980) Seasonal variation in population levels of *Phytophthora cinnamomi* Rands in soil in diseased, freely-drained *Eucalyptus marginata* Sm sites in the northern jarrah forest of south-western Australia. Protection Ecol 2:135-156.

Stahl W, Greaves R (1959) Report on a trip to Dwellingup, Western Australia, from 7.9.59 to 20.9.59 to investigate die-back in jarrah. Unpublished manuscript, Department of Parks and Wildlife Library, Perth.

Stoate TN, Bednall BH (undated) The jarrah and forestry practice. Unpublished manuscript, Department of Parks and Wildlife Library, Perth.

Stoate TN, Helms AD (1938) Stocktaking in the jarrah bush. Unpublished manuscript, Department of Parks and Wildlife Library, Perth.

Tainter FH, O'Brien JG, Hernández A, Orozco F, Rebolledo O (2000) *Phytophthora cinnamomi* as a cause of oak mortality in the state of Colima, Mexico. Plant Dis 84:394-398.

Underwood RJ, Murch JH (1984) Hygenic logging the northern jarrah forest. Australian For. 47:39-44.

Wallace WR (1966) Fires in the jarrah forest environment. J Roy Soc Western Australia 49:33-44.

Wallace WR (1969) Progress report on jarrah dieback research in Western Australia. Forests Department of Western Australia. Perth. Unpublished manuscript, Department of Parks and Wildlife Library, Perth.

Wallace WR, Hatch AB (1953) Crown deterioration in the northern jarrah forests. Unpublished manuscript, Department of Parks and Wildlife Library, Perth.

Waring HD (1950) Report on a brief investigation into the death of jarrah (*Eucalyptus marginata*) in the Dwellingup Division, Western Australia. Unpublished manuscript, Department of Parks and Wildlife Library, Perth.

Weste G, Taylor P (1971) The invasion of native forest by *Phytophthora cinnamomi*. I. Brisbane Ranges, Victoria. Aust J Bot 19:281-294.

Williamson J, Moore S, Warren C (2005) 1919 to 1935: a pivotal period for the forests of the south west of Western Australia. In Calver M, Bigler-Cole H, Bolton G, Gaynor A, Horowitz P, Mills J, Wardell-Johnson G. Proceeding of the 6th National Conference of the Australian History Society Inc. Millpress Science Publishers, Rotterdam.

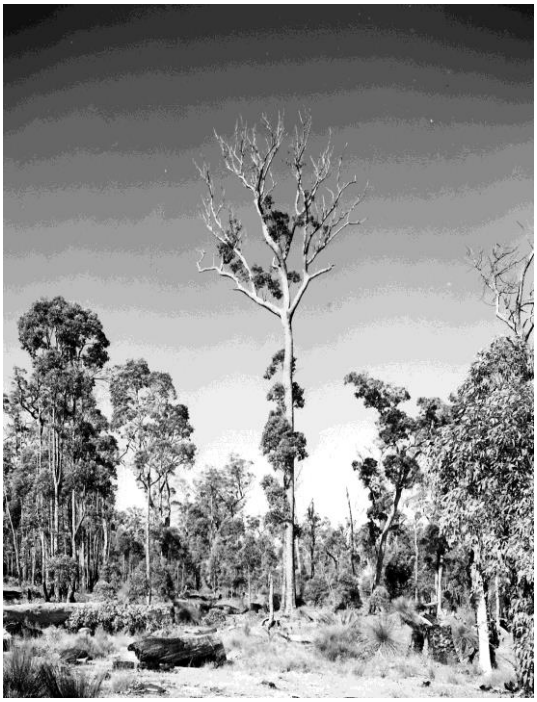
Zak B (1961) Aeration and other soil factors affecting southern pines as related to Littleleaf disease. USDA Forest Service, Technical Bulletin No. 1248.

Zentmyer GA (1964) Letter to Podger and Doepel, 21 October 1964. Unpublished manuscript, Department of Parks and Wildlife Library, Perth.

Zentmyer GA (1968) Report on jarrah dieback problem in Western Australia. Unpublished report to the Forests Department WA, May 1968, Department of Parks and Wildlife Library, Perth.

Fig. 1 Virgin jarrah forest, undated. ©Western Australian Department of Parks and Wildlife, image 970282, FA 603/24, serial no. F.D. 4448.

Fig 2. Jarrah log landing, undated. ©Western Australian Department of Parks and Wildlife, image 971429, serial no. F.D. 5188.



A

B

C

Fig. 3 Examples of symptoms in jarrah attributed to *P. cinnamomi* in the 1960s and 1970s. The captions are those on the photographs held in the Western Australian

Department of Parks and Wildlife library. A: Jarrah tree showing typical ‘dieback’ symptoms of *Phytophthora cinnamomi* attack, April 1970. ©Western Australian Department of Parks and Wildlife, image 970829, serial no. F.D 4825. B: Dieback destroyed forest, undated. ©Western Australian Department of Parks and Wildlife, image 972384, from Wallace (1969). C: Dieback area, 1968. ©Western Australian Department of Parks and Wildlife, image 970819, serial no. F.D 5374.